THE UNIVERSITY OF ROCHESTER
THE INSTITUTE OF OPTICS
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PROPERTIES OF MULTILAYER FILTERS

Interim Report

Covering the Period

March 1, 1966 to August 31, 1966

Research Grant No. NsG 308-63

with

National Aeronautics and

Space Administration

Washington 25, D.C.

Principal Investigator: P.W.Baumeister

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ABSTRACT

A multilayer band-pass filter of the design:

air (dielectric stack) M (spacer) M (dielectric stack) Q

has been fabricated and has a maximum transmittance of 0.67 and full width at 0.5 T_{max} of 84A. In this design, M represents an aluminum layer of 150A thickness and the dielectric spacer is cryolite. The possibility of using interference effects in thin films of indium, gold, and aluminum to produce filters in the spectral region below 1200A is investigated. From calculations based upon the published values of the optical constants of these materials, it is concluded that such filters are not feasible and would have poor rejection properties.

EXPERIMENTAL

The main effort in the fabrication of filters was to produce a band-pass filter with two metal films, as the design:

air (dielectric stack) M (spacer) M (dielectric stack) Q

where the M represents an aluminum layer and Q the Suprasil substrate. The method which is used to design this filter is described in the previous report of this grant, Semi-annual report of NsG 308-63, September 1, 1965 to February 28, 1966. In this report, this type of filter is called an "augmented 2-M filter" or alternatively a "T-Optimized 2-M filter." The latter term is more descriptive, because the addition of the dielectric stacks to either end of the filter optimizes its transmittance in the pass-band.

The experimental work was carried out by Mr. Robert Maier, as part of his M.S. thesis (June, 1966). The design procedure for such a filter is given in detail in this thesis, and does not differ markedly from that given in the previous report of this Grant.

The computed spectral transmittance T and the net energy flow ψ of the filter of Maier's design are shown in Fig. 1. In this filter, we have used the materials of cryolite (the "L" layer of index 1.35) and thorium fluoride for the "H" layer (index 1.55). The optical constants of aluminum were supplied by Mr. W. R. Hunter of the U.S. Naval Research Laboratory.

In order to check the accuracy of our monitoring of the thickness of the aluminum layers and also to ascertain that the aluminum is being evaporated under similar conditions in the vacuum as that of Hunter, Maier prepared a conventional "2-M" filter. Fig. 2 depicts the computed and measured transmittance of this filter. The computed transmittance is not corrected for the second surface reflectance loss of the substrate. We observe that the agreement between the computed and measured curves is not unreasonable. This strengthens our confidence that the conditions in the vacuum under which we are depositing our aluminum are similar to that of Hunter.

Maier made not a few trials in the evaporator to produce the T optimized 2M filter. One quite useful tool which was employed is the reflectance attachment for the Cary model 14 spectrophotometer, which enabled us to measure the reflectance of the final filter. This is illustrated by the spectral reflectance curves shown in Figs. 3 and 4. The computed spectral reflectance of this filter is shown in Fig. 3. If the "matching stacks" have been properly designed, then the reflectance should be zero (or close to zero) at the design wavelength of λ_o = 2536A. The measured spectral reflectance is shown in Fig. 4. If the reflectance is close to zero at λ_o, then the filter has been successfully fabricated. The ability to measure the reflectance presents a new possibility of improving a filter. Suppose that the reflectance at λ_o on the air side of a given filter is not zero, perhaps due to the fact that one of the aluminum films in the stack is too thick. It is possible to actually place the filter in the evaporator again and deposit more layers on it, thereby improving its transmittance. This, of course, only applies to the air side of the filter. If the reflectance is non-zero on the substrate side, there is no way this can be remedied. This procedure was used in producing the filter whose reflectance is shown in Fig. 4.

Fig. 5 shows the measured and computed transmittance of a "T optimized 2-M" filter. There are several differences between the computed and measured curves:

(1) The peak transmittance of the "pass-band" is located at 2536A for the computed curve and at 2710A for the experimental filter. As in the previous filters which we have produced, this is partially attributed to the fact that the optical monitoring beam is incident on

the monitor plate at about 15 degrees incidence. Another effect is that the film thickness is monitored by optical reflectance and we inevitably do not stop the deposition of a given layer until the reflectance maximum is past.

(2) The total width of the pass-band at $\frac{1}{2}T_{max}$, $\Delta\lambda$, is 80A and 84A for the computed and measured transmittance curves, respectively. Here, the more significent parameter is the "Q", $\lambda_o/\Delta\lambda$. The Q for the computed curve is 31.8 and 32.2 for the measured curve.

(3) There is a significant long-wave "leak" (near 2900A) in the experimental filter. This can only be attributed to errors in the thickness control of the films during deposition. However, we notice that on the short-wave side, the experimental filter is considerably more dense than the computer filter. This comparison is even more striking, if the transmittance of the experimental filter is shown on a density scale, as depicted in Fig. 6. The steep drop-off on the short-wave side is quite evident. It is unfortunate that this sharp cutoff is not on

the long-wave side of the transmittance band. This is because it is quite easy to find materials with a sharp absorption "edge" at shorter wavelengths, whereas materials which transmit at shorter wavelengths and absorb in the long wavelength region are practically unknown in this spectral region.

These experimental filters were completed in May of this year. It was evident that the time had arrived to improve the monitoring system and to overhaul the vacuum chamber in which the films are deposited. The chamber has been used for three years without such a major overhaul and the thickness of the films which were deposited on the parts of the vacuum chamber rivaled the massive stalactites in Carlsbad caverns. This overhaul has consumed our efforts during the remainder of the summer months. We also have been installing a McPherson model 225 vacuum U.V. monochromator and are designing an attachment which will enable us to measure the reflectance and transmittance of filters. At present, we have been limited in our measurements to wavelengths longer than 1900A, which is the practical "cutoff" of the Cary Model 14 spectrophotometer. This vacuum U.V. monochromator will enable us to extend our measurements to 1200A, which is the transmission limit for the lithium fluoride substrates which we are using.

THEORETICAL

The theoretical problems which we investigated are: (1) The design of a "1-M" band-pass filter (at 1849A), (2) A study of possible thin film materials which could be used as components of filters in the spectral region below 1500Å.

The design procedure used for the 1-M filter is described in a previous report of this grant. The transmittance contours in the admittance plane are shown in the report of NsG 308-63 for September 1, 1965 to February 28, 1966. Using these contours, it is a simple task to design the "admittance matching" stacks for such a filter. The resulting computed spectral transmittance of the filter is shown in Fig. 7.

We next investigated thin film materials which could possibly be used in the vacuum ultraviolet spectral region. This region can be divided into two sub-regions: In the long-wave region (at wavelengths longer than 1300A), there are materials such as lithium fluoride and calcium fluoride which are relatively transparent. This means that it is still possible to construct either metal-dielectric-metal interference filters (using aluminum) and also "1-M" filters (similar to the type described in the foregoing paragraph) in this spectral region. However, we note that the properties of this filter depend on the fact that the aluminum layer is employed to absorb and/or reflect the radiation at wavelengths outside of the pass band and that there are available two or more materials of different refractive index which can be employed as an "admittance matching" stack or a dielectric spacer to construct the remainder of the filter.

In the spectral region near 1200A only the lithium fluoride is transparent and at 1100A this material is absorbing. There remains the question, are there any combinations of absorbing optical materials which could be combined to construct a filter below 1100A?

In order to answer this question, one must know the optical constants for materials in this spectral region. These are rather scarce. The optical constants of aluminum were measured by Hass, Madden, et al. and more recently by W. R. Hunter of the Naval Research Laboratory. Hunter also measured the n and K of indium and gold.

At the present time, the only types of filters which are used in this spectral region are unbacked films of aluminum and films of indium. However, the question remains whether combinations of these materials could be employed to produce optical filters.

Using the optical constants which were generously supplied to us by W. R. Hunter, we computed the transmittance and maximum energy flow, ψ_{max}, of the materials aluminum, indium, and gold.

In order to be used as a component layer of a band-pass filter, two attributes must be possessed by a film material:

(1) A substantial peak transmittance.

(2) A good rejection at wavelengths outside of the pass-band region.

As is pointed out by Berning and Turner,[1] a measure of the peak transmittance is the energy flow ψ is a function of the thickness and optical constants, n and k, of the film, as well as the admittance of the medium which surrounds the film. However, for a film of given optical constants and specified thickness, there is maximum value of ψ which is ψ_{max}. The peak transmittance of the film can never exceed this value of ψ_{max} and thus this parameter is useful in estimating the peak transmittance of the filter containing this film.

A parameter which is useful in estimating the rejection of a filter is the transmittance of an absorbing layer which is surrounded on either side by medium unit admittance. In other words, this is the transmittance of a film which is stripped from its substrate and is surrounded on either side with a vacuum. Although such a condition is never achieved in practice, this transmittance still is nevertheless a useful criterion in estimating the rejection of the absorbing

[1] P.H. Berning & A.F. Turner, J. Opt. Soc. Am. 47, 230 (1957).

film, when it is employed in a filter. There is little difference between the transmittance of this unbacked film and the film when it is attached to the substrate.

In the following section of this report, the transmittance T (for an unbacked film) and maximum energy flow ψ_{max} is computed for films of indium, gold, and aluminum.

Fig. 8 depicts T and ψ_{max} for aluminum of thickness 200A and 500A. The abscissa extends from 50,000 cm^{-1} (2000A) to 150,000 cm^{-1} (666A). From this curve it is concluded that aluminum is quite an effective material to use in a "1-M" or "2-M" type of filter at wavelengths longer than 1200A, but it does not have enough "rejection" at shorter wavelengths. The effect of the thin layer of aluminum oxide on the surface of the aluminum is not taken into account in these calculations. Its effect would be to decrease the peak transmittance.

Fig. 9 depicts computed curves for T, ψ_{max} for indium films of thickness 400A and 1000A. Only in the spectral region near 1000A (100,000 cm^{-1}) does this material have a reasonably high maximum transmittance and good rejection. At shorter wavelengths, ψ_{max} and T are nearly equal and there is little hope of using this material as a filter in this region.

Fig. 10 shows the computed ψ_{max}, T for a gold film of thickness 200A. Not only is the ψ_{max} rather low at all wavelengths, but the rejection is not particularly good. Thus we conclude that this material is particularly unpromising as an optical filming material for this spectral region.

At present, optical filters such as unbacked films of aluminum indium in the region below 1000A function by utilizing the selective absorptance and transmittance of these materials. The transmittance of the "pass-band" is due to change with wavelength optical properties of the film itself, rather than any interference effects in the thin film. The results of the computations (shown in Figs. 8, 9, 10) indicate that there is not much hope of using interference effects in such films to produce filters.

Personnel:

P. W. Baumeister, Principal Investigator

32% in March, April, May.

Two months during the summer.

Mr. D. H. Harrison, Graduate Research Assistant

Six weeks during the summer.

Mrs. Susan Chadwick, Student Programmer

Four weeks during the summer.

Captions to the Figures

1. Computed spectral transmittance T and energy flow ψ for the band-pass filter whose design is shown. In this design:

   L represents QWOT at λ_o of index 1.35.

   H represents QWOT at λ_o of index 1.55.

   L_1' is 0.825 QWOT

   L_2' is 1.71 QWOT

   L_3' is 0.816 QWOT

   The index of the QUARTZ substrate is 1.48.

2. Computed and measured transmittance of a filter of design

   air M D M Quartz

   where M is 150A of aluminum and the cryolite dielectric spacer has an optical thickness of 872A.

3. Computed spectral reflectance from the air side (i.e. COATED SIDE) and substrate side of the filter whose design is shown in Fig. 1.

4. Measured spectral reflectance of a band-pass filter whose design is similar to the filter whose design is shown in Fig. 1.

5. Measured and computed spectral reflectance of T-Optimized 2-M filters.

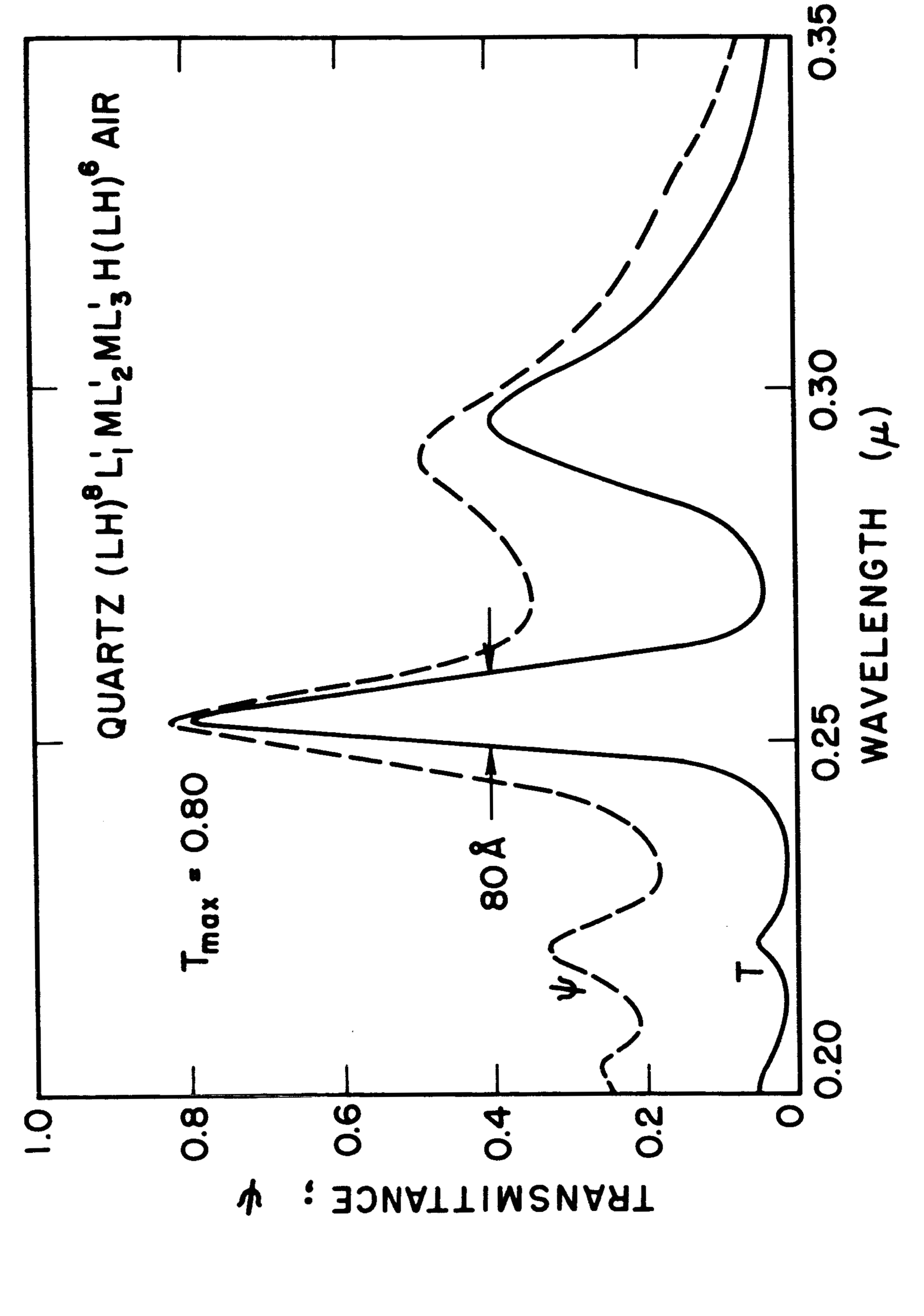
6. Measured spectral transmittance of "2-M" and a "T-Optimized 2-M" filters. The 2-M curve is the same as shown in Fig. 2, but is plotted on an optical density scale. The transmittance of the "T-Optimized 2M filter" is the same as the measured curve shown in Fig. 5.

7. Computed spectral transmittance of a "1-M" filter designed to transmit the 1849A resonance line of mercury. The aluminum is 250A in thickness and the H and L layers represent quarter-waves of thorium fluoride and cryolite, respectively.

8. Computed maximum energy flow, ψ_{max}, and transmittance T of an unbacked film of aluminum of thickness 200A (dashed curve) and 500A (solid curve).

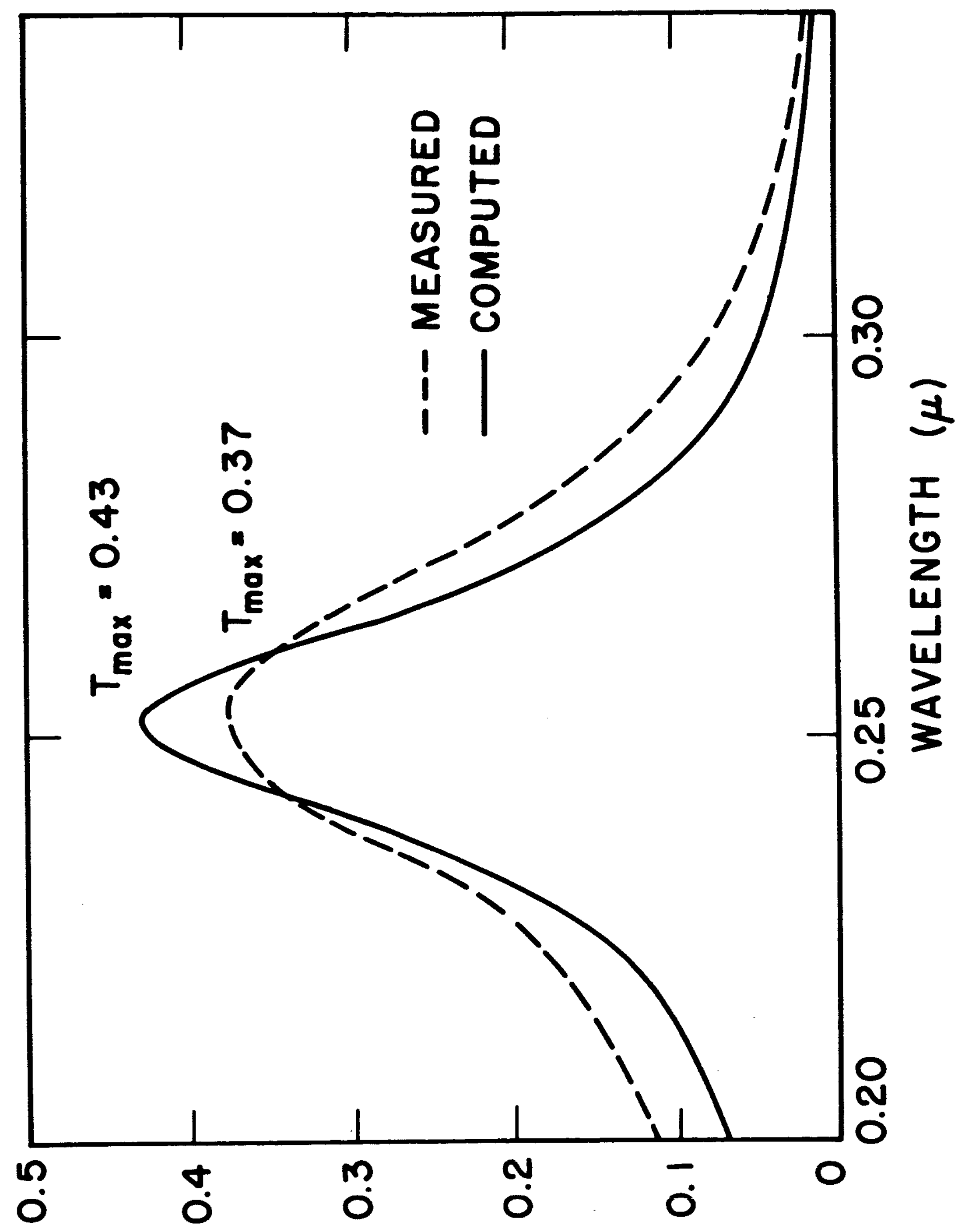
9. Computed maximum energy flow, ψ_{max} and the transmittance T (of an unbacked film) of films of indium of thickness 400A (dashed curve) and 1000A (solid curve).

10. Computed maximum energy flow, ψ_{max}, and transmittance T (of an unbacked film) of a gold film 200A in thickness.



QUARTZ $(LH)^8 L_1' M L_2' M L_3' H (LH)^6$ AIR
$T_{max} = 0.80$
80 Å
ψ
T
WAVELENGTH (μ)
TRANSMITTANCE ; ψ
0.20
0.25
0.30
0.35
0
0.2
0.4
0.6
0.8
1.0

FIG 1



TRANSMITTANCE
0.5
0.4
0.3
0.2
0.1
0
0.20
0.25
0.30
WAVELENGTH (μ)
T_{max} = 0.43
T_{max} = 0.37
MEASURED
COMPUTED

FIG 2

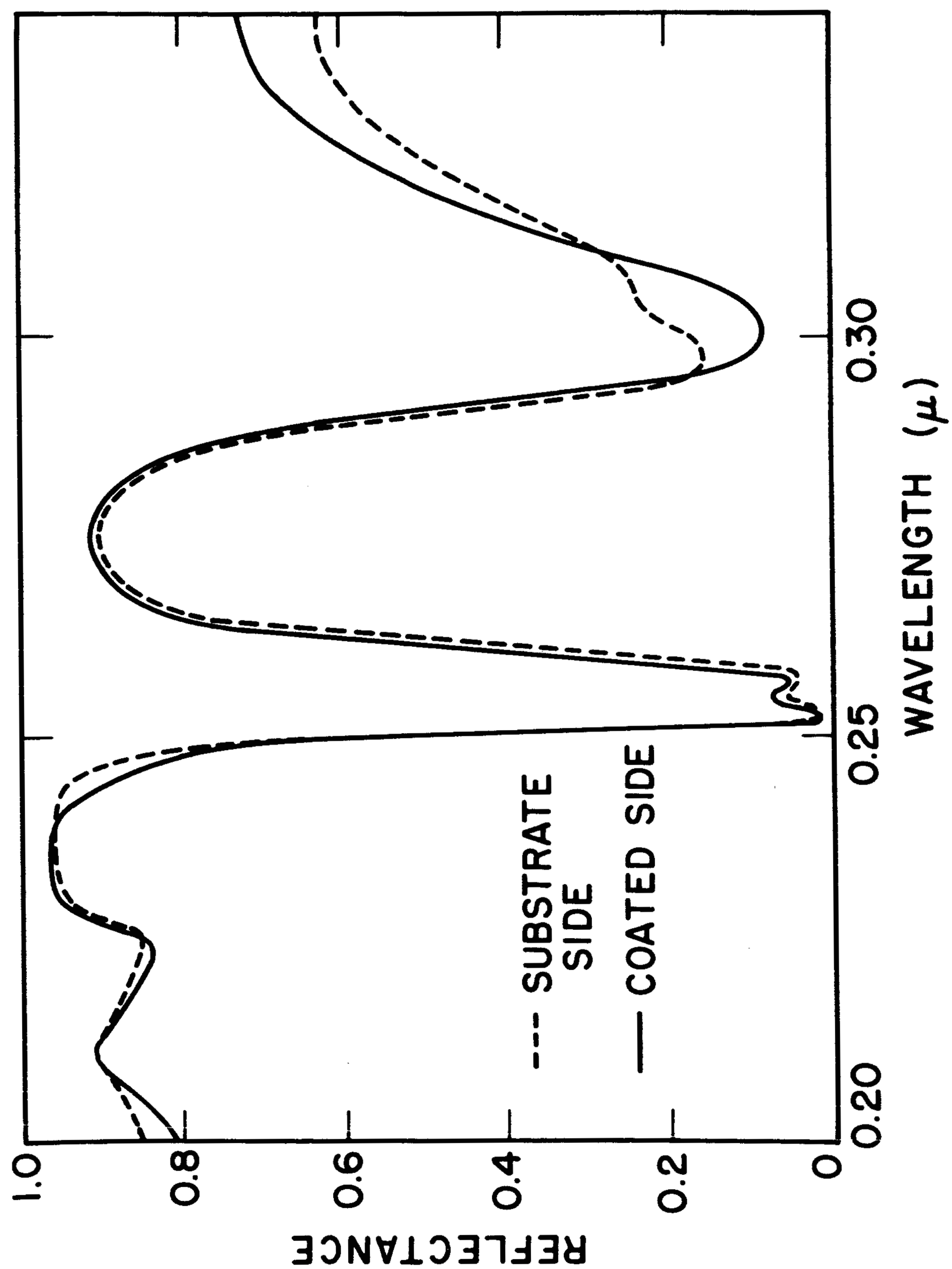

REFLECTANCE
1.0
0.8
0.6
0.4
0.2
0
0.20
0.25
0.30
WAVELENGTH (μ)
SUBSTRATE SIDE
COATED SIDE

FIG 3

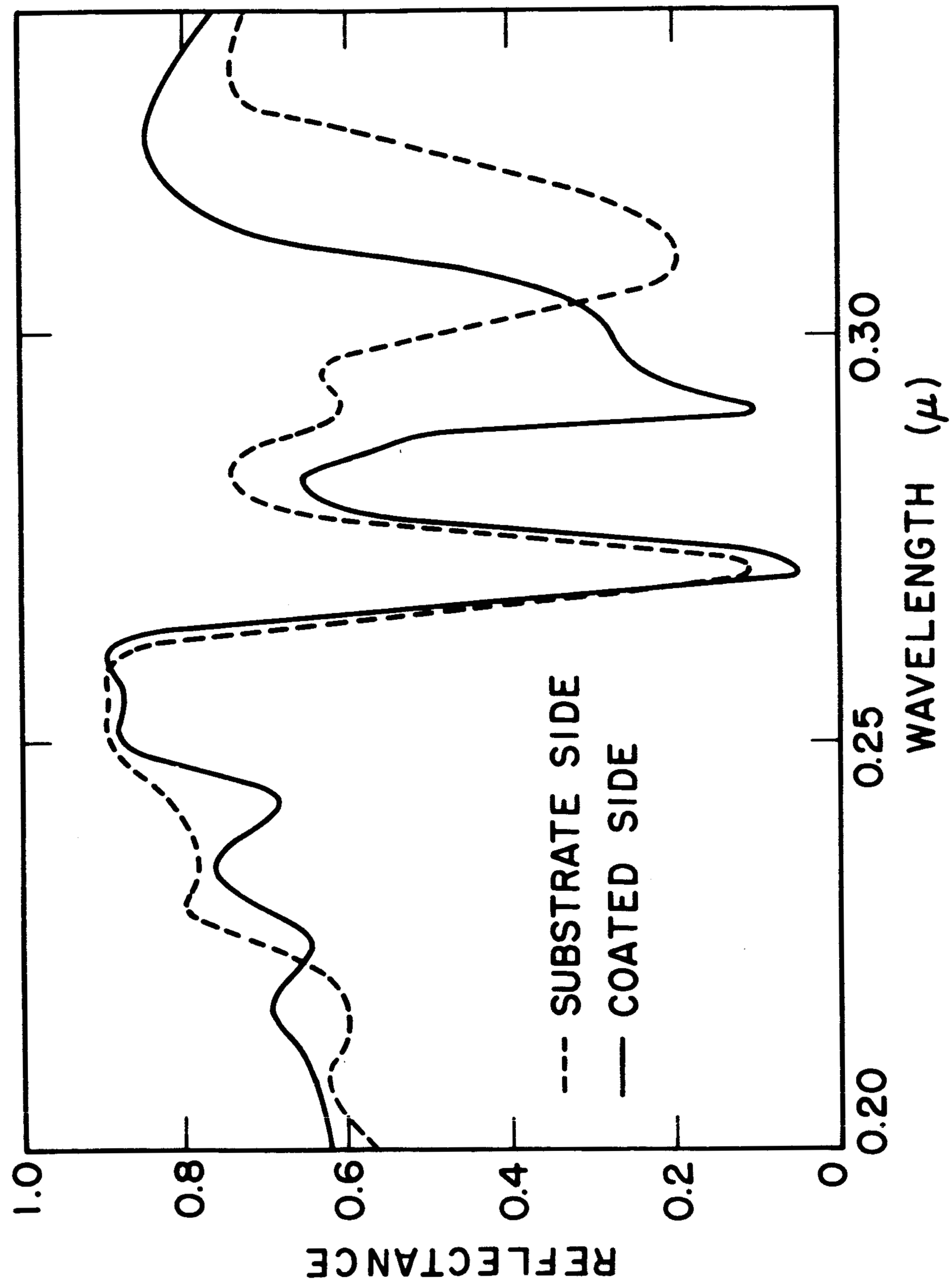
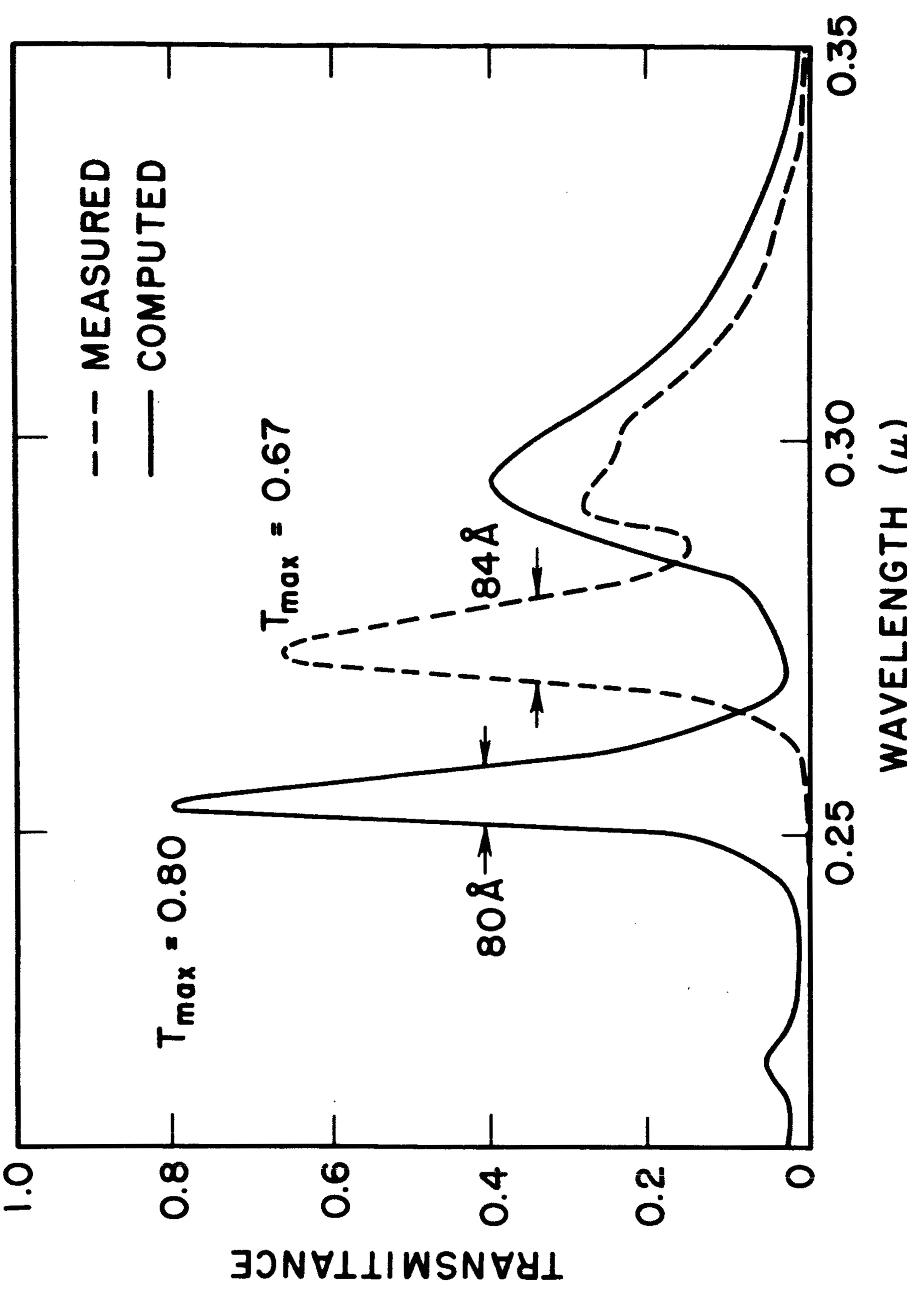
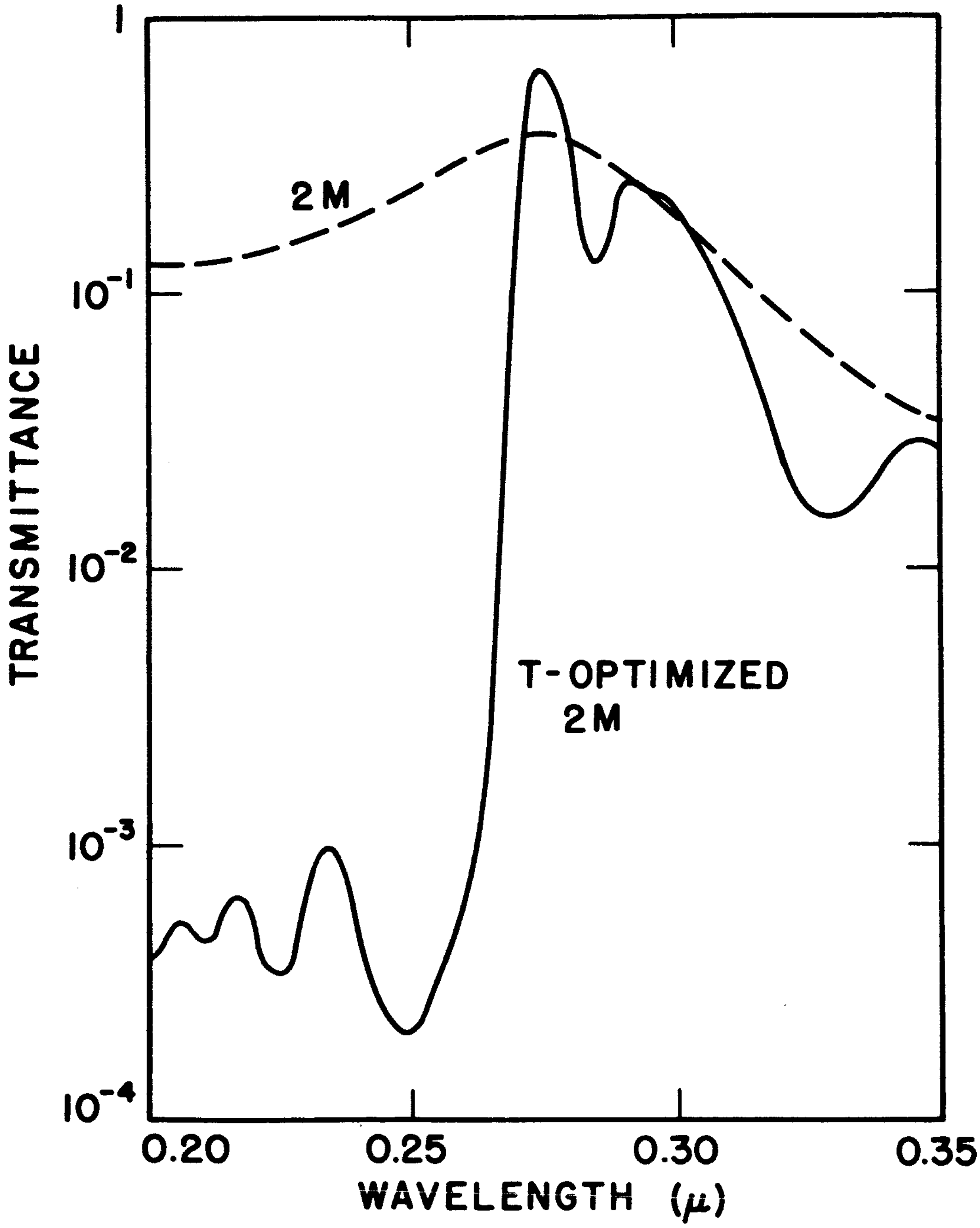

REFLECTANCE
1.0
0.8
0.6
0.4
0.2
0
0.20
0.25
0.30
WAVELENGTH (μ)
--- SUBSTRATE SIDE
— COATED SIDE

FIG 4



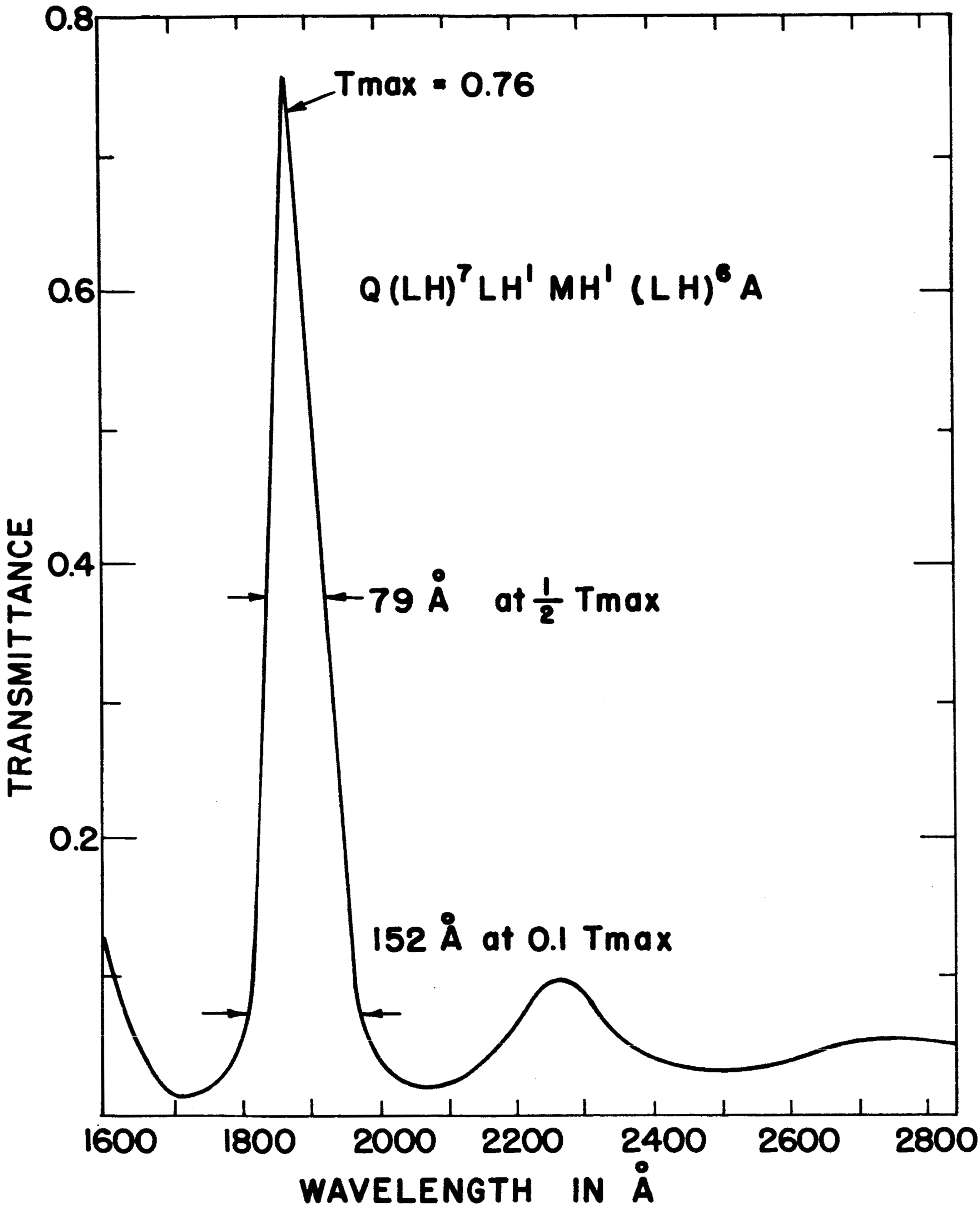
MEASURED
COMPUTED
T_{max} = 0.80
T_{max} = 0.67
80Å
84Å
TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0
0.25
0.30
0.35
WAVELENGTH (μ)

FIG 5



1
2M
10^{-1}
10^{-2}
10^{-3}
10^{-4}
TRANSMITTANCE
T-OPTIMIZED
2M
0.20
0.25
0.30
0.35
WAVELENGTH (μ)

FIG 6



0.8
0.6
0.4
0.2
TRANSMITTANCE
Tmax = 0.76
Q (LH)^7 LH^1 MH^1 (L H)^6 A
79 Å at $\frac{1}{2}$ Tmax
152 Å at 0.1 Tmax
1600
1800
2000
2200
2400
2600
2800
WAVELENGTH IN Å

FIG 7

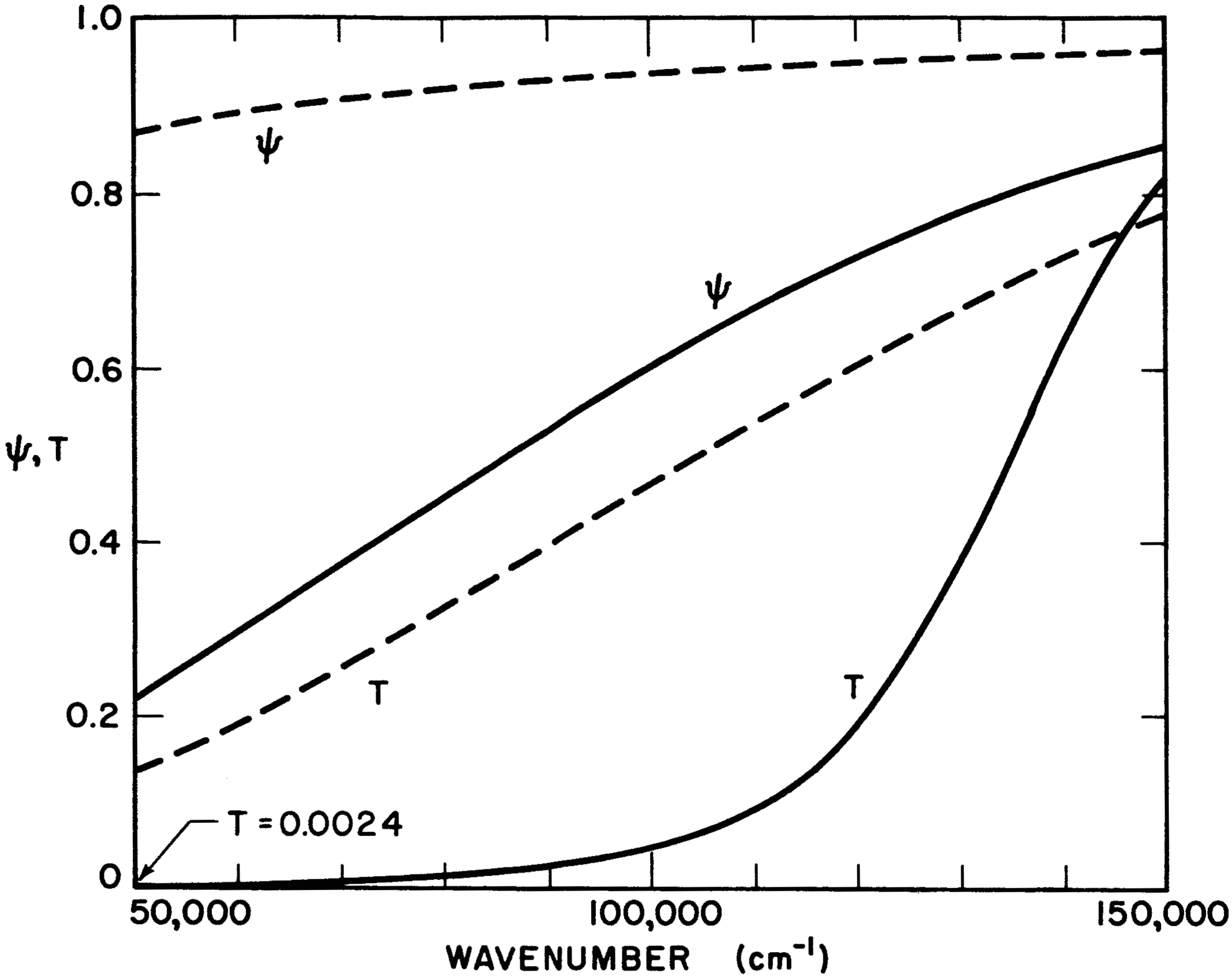

1.0
0.8
0.6
0.4
0.2
0
ψ, T
ψ
ψ
T
T
T = 0.0024
50,000
100,000
150,000
WAVENUMBER (cm⁻¹)

FIG 8

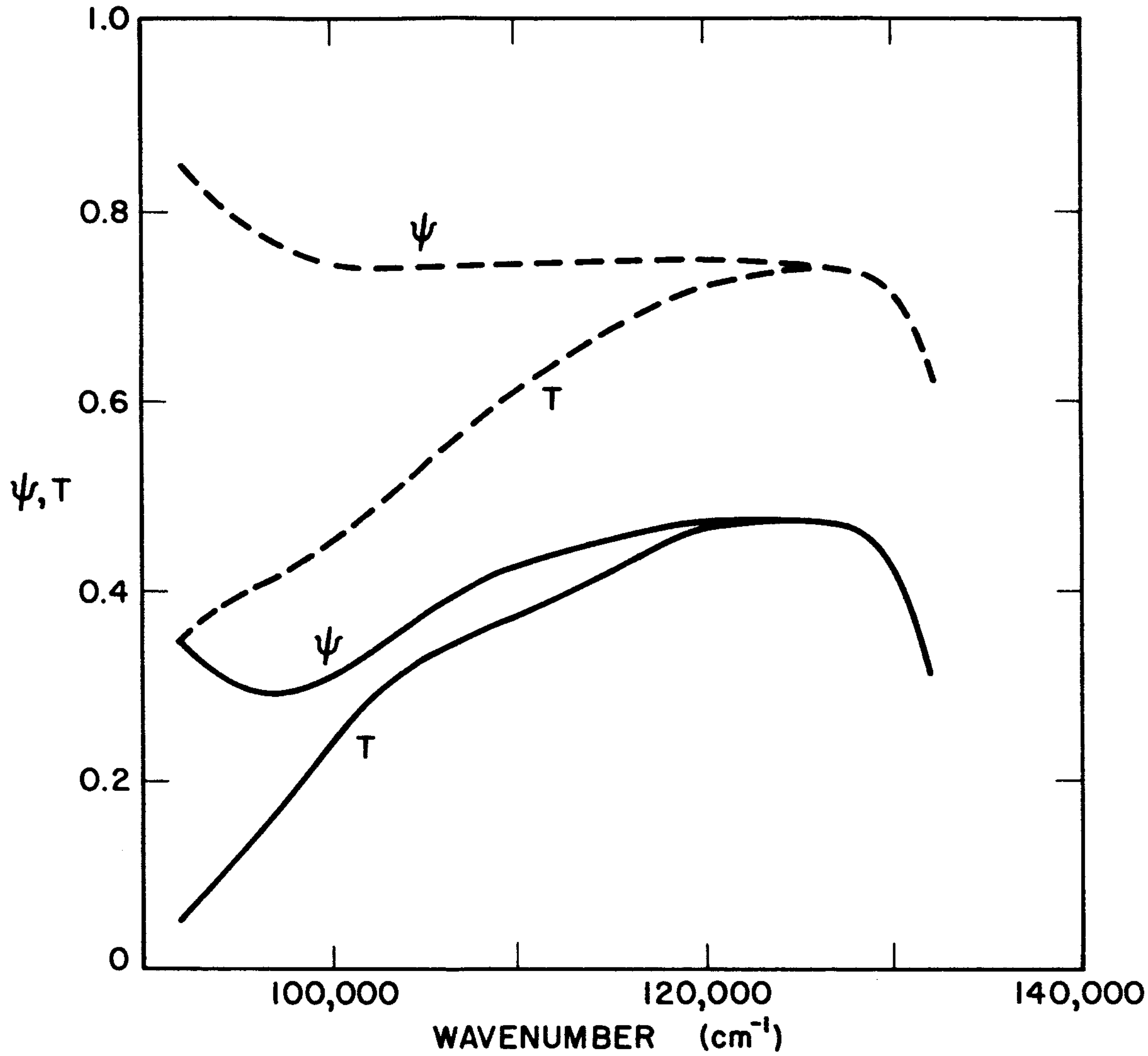


FIG 9

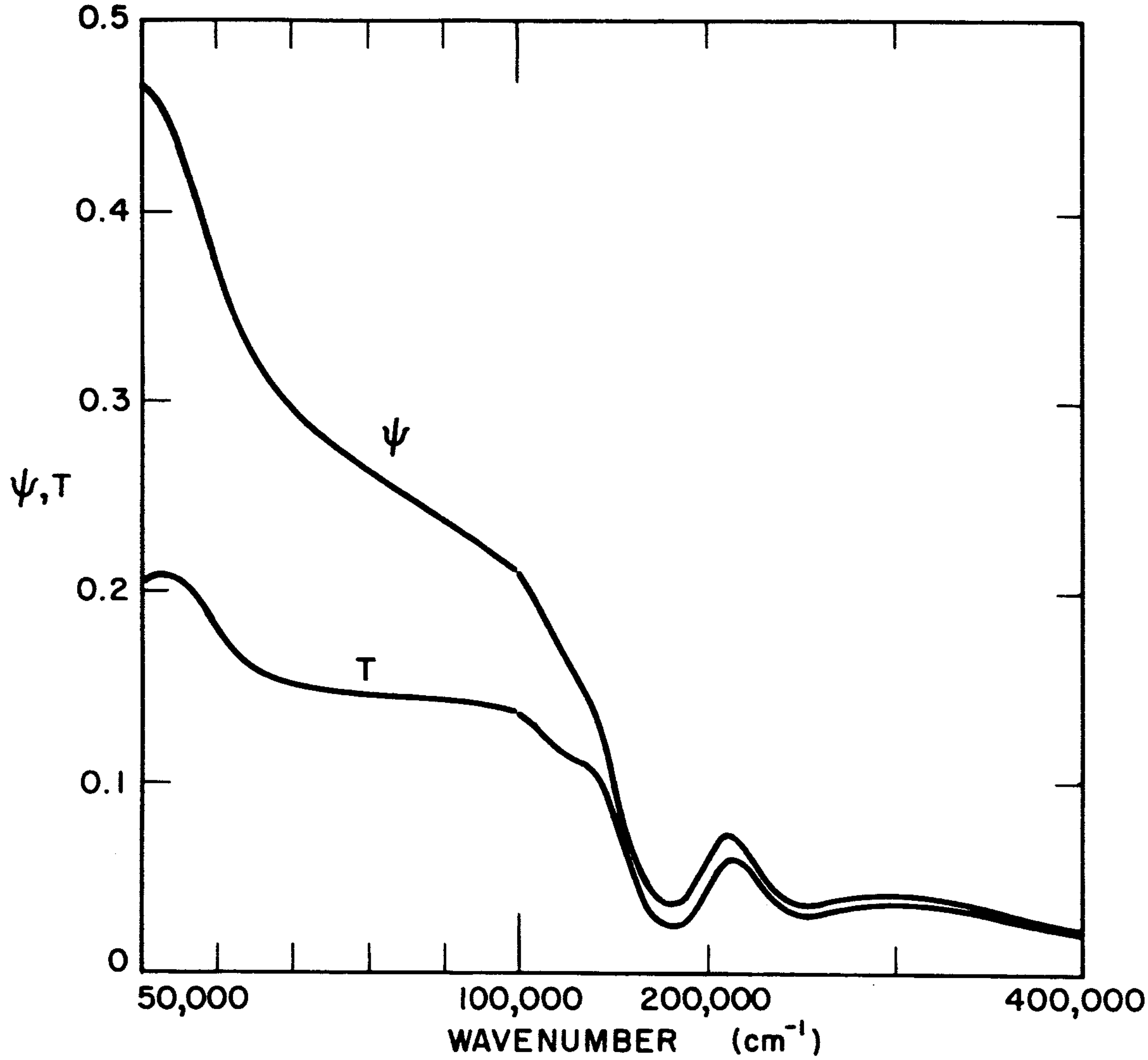

0.5
0.4
0.3
0.2
0.1
0
ψ,T
ψ
T
50,000
100,000
200,000
400,000
WAVENUMBER (cm⁻¹)

FIG 10